DEVELOPMENT OF A FOREST SITE QUALITY CLASSIFICATION MODEL FOR MINE SOILS IN THE APPALACHIAN COALFIELD REGION[1]

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Abstract. The Appalachian coalfields occur largely under rugged mountains covered by native hardwood forests. These forests, soils, and bedrock are removed by the surface mining process. Surface mines are not typically reclaimed to a managed forest land-use, but are often seeded with non-native grasses and legumes, or with pines, black locust, and shrubs for unmanaged forest land. Surface mining and reclamation techniques since the passage of the Surface Mining Control and Reclamation Act of 1977 (SMCRA) create highly compacted mine soils with high coarse fragment content, low organic matter, and high pH, which inhibits native forest reestablishment. The purpose of this study was to develop a forest site quality classification model to advise landowners on the production potential and feasibility of reforesting their mined lands with white pine (*Pinus strobus* L.). Ten selected physical, chemical, and site properties were assessed and a model was developed using variables that were the most highly correlated with the growth of 10- to 18-year-old white pines established on post-SMCRA surface-mined sites. A model with soil pH, texture, density, and rooting depth variables yielded a coefficient of determination of 0.71. Sufficiency curves were used in a productivity index (PI) model to classify reclaimed surface-mined land into one of five forest site quality classes (FSQC). A site index (SI_{50} = dominant tree height at age 50) for white pine was estimated for each class, and this measure of productivity may be used to aid in management decisions regarding reforestation of surface mines in the Appalachian coalfields.

Additional Key Words: forest productivity, reclamation, reforestation, site quality, productivity index.

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Introduction

Surface mining for coal has been taking place in the Eastern United States since the late 1940s, and the Appalachian Plateau region of Virginia, Kentucky, and West Virginia contains a large source of coal that can be profitably extracted with surface mining techniques. Due to safety and environmental concerns, many regulations have been emplaced to ensure the stability and productivity of post-mining landscapes. The Surface Mining Control and Reclamation Act (SMCRA) of 1977 requires coal companies to return mined land to its "approximate original contour" (AOC), requires topsoil or an approved topsoil substitute to be replaced, and requires the land to be able to support vegetation at its original productivity level or better (Public Law 95-87). However, since hayland and pasture are considered higher-order land uses, the law allows coal companies to seed the area to herbaceous forages, leading to a decline in the native forests that historically occupied the landscape.

There is no forest productivity standard currently enforced for mined land reclaimed under a regular forestland permit. Only a stocking standard or a minimum number of trees surviving for the five-year bond period is required. In addition to the stocking standard, we believe that mined land reclaimed to forestry should meet a minimum productivity standard in order to satisfy the intent of the SMCRA to return mined land to its original capability level. Research shows that forest land productivity can be fully restored. Ashby (1984) stated that mined land could actually improve tree growth because mine soils have greater porosity, improved water movement, fewer rooting restrictions, better pH levels, and greater nutrient availability than some native soils. Recent research by Rodrigue and Burger (2004) corroborates Ashby's observations. Therefore, if mined lands are reclaimed with the right combination of soil physical and chemical properties, forest site productivity could be restored.

Because it is difficult to evaluate forest productivity with only five years of growth obtained during the normal bond period, the soil and site conditions that are known to affect tree growth might be used to predict a site's forest productivity potential. Soil and site conditions are commonly used to judge forest productivity where there are no trees present for direct estimations of forest growth rates or productivity (Carmean, 1975). The same approach could be used to estimate the productivity of recently reclaimed mined sites, given that soil and site conditions that influence tree survival and growth have been extensively studied and described.

In recently reclaimed mine soils formed from non-oxidized rock, the pH is often high (> 7) due to the lack of weathering. These values may be high enough to reduce the availability of B, Cu, Zn, Fe, and Mn (Brady and Weil, 1999). Torbert et al. (1990) found a strong inverse relationship ($r^2 = 0.86$) between tree volume and mine soil pH when studying pine growth on different spoil types. The pH values ranged from 5.7 in the pure sandstone spoils to 7.1 in the pure siltstone. Furthermore, a low pH negatively affects the growth of herbaceous ground cover seeded during reclamation, reducing the competition with trees.

Soluble salt concentration (or electrical conductivity, EC) has been recognized as a factor that is often an issue in the reforestation of mine soils (Torbert et al., 1988b; Burger et al., 1994; Andrews et al., 1998; Rodrigue and Burger, 2004). Tree growth decreases as EC levels increase. Andrews et al. (1998) found that total soluble salts ranged from 0.02 to 1.97 dS/m across 78 mined sites. When values exceeded 1.00 dS/m, total salts became one of the most important chemical properties affecting white pine growth on mine soils.

Torbert et al. (1988a) concluded that physical soil properties were more influential than fertility on 8-year-old white pine (*Pinus strobus* L.) grown on reclaimed mine soil benches in southwest Virginia. Important physical properties that affect successful reforestation of mine soils are coarse fragment content, particle size, bulk density, and color (Vogel, 1981). In most soil-site evaluations, the most important factors related to forest productivity are available soil moisture and the growing space for tree roots (Aydelott, 1978; Sharma and Carter, 1996; Bussler et al., 1984; Potter et al., 1988; Rodrique, 2001).

Mine soils commonly have higher bulk densities and lower porosities than native soils due to heavy traffic associated with grading (Thurman and Sencindiver, 1986). This compaction due to traffic also results in increased resistance to roots, impeded infiltration and drainage, reduced aeration, and other factors that are detrimental to tree survival and growth (Ruark et al., 1982). Torbert and Burger (1990) reported tree survival data on a rough-graded area and a leveled smooth-graded area as 70% and 42%, respectively.

High coarse fragment contents are characteristic of the eastern coalfield region and are often a potential growth-limiting problem because of the reduced total soil volume, lower water holding capacity, rapid drainage, and potentially droughty conditions due to water held at low water potentials (Pedersen et al., 1978; Schoenholtz et al., 1992; Sobek et al., 2000). Bramble (1952) reported that at least 20% of soil-sized particles must be present for trees to survive.

A sandy loam texture is optimum for tree growth on mine soils (Burger and Zipper, 2002). Silty soils and soils with high clay content are more easily compacted and less aerated than soils dominated by sand-sized particles. Poor aeration and drainage are chief causes of poor tree survival and growth.

Mine soil color (Munsell Color Charts, Kollmorgen Instruments Corporation, Newburgh, NY) indicates the oxidation and weathering of different rock types. A soil chroma of ≥ 3 is a good indication that oxidation and chemical weathering processes that release nutrients from the hard rock have taken place (Sobek et al., 2000; Haering et al., 2004). Materials with a color value ≤ 3 contain high amounts of carbon and often contain high amounts of sulfur that may be a source of extreme acidity (Sobek et al., 2000).

Rock type is a major factor that influences many other soil properties and is largely responsible for forest productivity (Andrews, 1992; Ashby, 1984; Preve et al., 1984; Torbert et al., 1988a; Torbert et al., 1990). Oxidized sandstone spoil is considered to be the best parent material for the production of forest trees due to its resistance to compaction, increased macroporosity, slight acidity, low soluble salt level, and quick response to physical weathering processes (Torbert et al. 1990; Hearing et al., 1993). Siltstone and shale weather into finer particles and are generally more susceptible to compaction and have fewer macropores, a higher pH, and higher levels of soluble salts than most sandstone spoils. In a study by Torbert et al. (1988a) of hybrid pine growth on different rock mixtures, 4-year-old trees had an average height, diameter, and volume of 146.2 cm, 40.4 mm, and 685 cm^3, respectively, on oxidized sandstone spoil. On siltstone spoil, the values reported were 84.8 cm, 21.8 mm, and 123 cm^3. After five years, Torbert et al. (1990) concluded that overall survival was not significantly affected by rock type, but tree volume was. About 1.2 m of uncompacted sandstone material is needed to produce a mine soil of high quality and productivity for native trees (Burger and Zipper, 2002).

Total soil depth positively influences the productivity of mine soils through increased rooting depths and greater available water holding capacity (Torbert et al., 1994; Andrews et al., 1998).

Andrews et al. (1998) found that rooting depth was the mine soil property most strongly related to height growth for 78 white pine plantations growing on reclaimed mine soils. Torbert et al. (1988b) found that the rooting volume index (RVI = rooting depth x percent fraction < 2 mm) accounted for almost 50% of the variation in tree height for 8-year-old white pines.

With the requirement of returning the land to AOC, reclaimed mine spoil is graded with large equipment. Therefore, the slope of a site may indicate the degree of compaction. Slopes greater than 25% are difficult to traverse with large equipment, and the soils on steep slopes are consequently less compacted and have a deeper rooting depth than soils on flat areas (Andrews et al., 1998).

The aspect of the slope has an influence on the temperature and water relations (evaporation and transpiration) of the soil. Southwest slopes receive the most direct sunlight during the growing season, which increases evaporation and soil temperatures, causing even drier conditions on mine soils that are potentially droughty already. Northeast aspects are considered to be the best sites for tree growth due to their mesic site conditions (Burger et al., 2002).

This brief synthesis of past research demonstrates known relationships between tree growth and a number of measurable site and soil properties. We believe these properties can be evaluated on a given mined site and that their values can be combined for an estimate of forest site quality (FSQ). Furthermore, we believe this estimate of FSQ could be used to judge a reclaimed mined site relative to its suitability for forest trees and its potential productivity. Agronomic researchers have successfully combined soil properties in models to estimate crop production (Neill, 1979; Kiniry, 1983; Pierce et al., 1983):

$$\mathrm{PI} = \sum_{i=1}^{r} (\mathrm{A} \times \mathrm{B} \times \mathrm{C} \times \mathrm{D} \times \mathrm{WF})_i \qquad \textbf{(1)}$$

where PI is a productivity index scaled from 0 to 1; A, B, C, and D are sufficiency levels (scaled from 0 to 1) of soil properties known to influence crop production; and WF is a weighting factor that adjusts the relative importance of different soil layers through the profile. The product was summed over *r*, the number of soil layers within the total rooting depth.

Foresters have modified this model to make it specific to forest land productivity (Gale, 1987; Henderson et al., 1990):

$$\mathrm{PI} = \sum_{i=1}^{r} (\mathrm{A} \times \mathrm{B} \times \mathrm{C} \times \mathrm{D})^{1/4} \times \mathrm{WF})_i \times (\mathrm{S} \times \mathrm{Cl})^{1/2} \qquad \textbf{(2)}$$

where S and Cl are sufficiency factors for slope and climate respectively, and the geometric mean (1/4 in the exponent) of the product is taken to assure equal weighting of soil properties.

A simple mine soil quality model that incorporates key soil properties most influencing forests might be used in a similar fashion by reclamation personnel to evaluate the suitability of reclaimed sites for forestry post-mining land uses. Foresters and reclamation managers also need site quality information to make silvicultural recommendations for abandoned mined land that is to be managed for forest production. Therefore, the objectives of this study were to: (1) develop a soil-based model for estimating forest site quality on reclaimed surface mined land; and (2) verify the accuracy of the model using white pine stands growing on mined land.

Materials and Methods

Model Development and Validation

Based on previous research reviewed above, 10 soil and site variables were selected for possible inclusion in a forest site quality model. General sufficiency curves defining the relationship between tree growth and levels of soil properties were developed based on past and current research. A site quality estimate was made using Equation 2 above, the productivity model reported by Gale (1987).

The same soil and site properties were measured or estimated to test the general classification model for white pine on post-SMCRA reclaimed mine lands. Fifty-two white pine sites ranging from 10 to 18 years old were sampled at sites in Wise County, Virginia, and Nicholas, Mercer, and Wyoming Counties, West Virginia, for 10 soil and site variables and for site index (SI = dominant tree height at age 50) of white pine.

Field Measurements

The pH, soluble salt content (as indicated by electrical conductivity, EC), texture, color, rock type, coarse fragment (CF) volume percent, soil density, potential rooting depth, slope, and aspect were estimated at several (three to five) locations within each site and averaged for a representative value. The sampled area varied from 9 m^2 to 36 m^2 depending on tree and stand diversity and the uniformity of soil types.

The dominant soil material in the upper 20 cm was evaluated. The pH and EC were measured with a Hanna HI 9812 field meter (Hanna Instruments Inc., Woonsocket, RI) in pH units and µS/cm, respectively. The soil hue, value, and chroma were recorded using Munsell Color Charts (Kollmorgen Instruments Corporation, Newburgh, NY). On sites where an A horizon had formed on the surface, the Munsell color was read below the zone of apparent organic matter accumulation. Soil texture was estimated by standard field methods. Rock type was recorded as the percent of sandstone by volume of all rocks in the sample area. The CF percent was estimated visually as the volume percent of fragments greater than 2 mm in size. Texture, rock type, and CF volume estimates were occasionally checked and verified by collecting representative samples and conducting lab analyses.

No completely quantitative method was found to accurately predict mine soil bulk density because of the high number of coarse fragments. Conventional bulk density measurements require laboratory calculations of CFs and moisture contents and are too time-consuming for practical field measurements. Therefore, the general density of the upper 20 cm was estimated based on the average penetration depth of a sharpshooter (tapered shovel with rounded tip blade 14 cm wide and 40 cm long) along with observations of soil rupture resistance and CF type and volume. The sharpshooter was stepped on using a steady force from the weight of a 70-kg person, and the depth and ease in which it penetrated the soil was noted along with the associated soil properties listed above. The following guides were used to estimate five general density classes: If the sharpshooter penetrated easily to 25 cm or more, a density class of “very low” was assigned; if penetration was 16 to 25 cm with slight resistance, a density class of “low” was assigned; if penetration was less than 15 cm with moderate resistance, a density class of “moderate” was assigned; if penetration was less than 5 cm with strong resistance, a density class of “high” was assigned; and if penetration was less than 2 cm, a density class of “very high” was assigned. The density class was decreased by one class in soils with an estimated CF content greater than 50%, provided that the moist rupture resistance (a.k.a. moist consistence class) at the depth of maximum sharpshooter penetration was not very firm or extremely firm (Soil Survey Division Staff, 1993) as confirmed by shallow pit excavations. In moist soils with low CF content and textures finer than sandy loam, the density was increased one class because those soil conditions allow sharpshooter penetration into soil that has moist rupture resistance of very firm or extremely firm as confirmed by shallow pit excavations. In extremely dry soils, no adjustment was made. Along with the rupture resistance, fine root growth widely spaced or matted between aggregates, and large aggregate size, were used to confirm that the soil was dense.

The potential rooting depth (cm) was determined by using a screw auger (round tip screw head 16 cm long and 5 cm wide, with a bit consisting of three complete turns on a shaft 97 cm long) and turning it into the ground until significant resistance was felt (more than upper body strength was required) or complete refusal was reached. Layers with “bridging voids” (large air gaps between rocks), greater than 90% CFs, and essentially no soil was considered root-limiting, along with dense, compacted layers.

Site factors were measured at each sample location. Percent slope was measured using a standard clinometer. Aspect was measured as an azimuth on slopes greater than 15% using a standard compass.

At each sample point the nearest two to four trees were measured using the growth intercept model developed by Beck (1971), in which the lengths of the first five internodes (distance between whorls of branches) beginning at breast height (1.4 m) are measured and converted to a site index (Equation 3). Waiting until the tree reaches breast height minimizes the effects of strong competition by ground cover on tree seedlings.

$$SI = 26 + 6.6(\text{5-year intercept}) \qquad \mathbf{(3)}$$

where SI = white pine site index (predicted tree height in feet at age 50); 26 and 6.6 are coefficients; and 5-year intercept = total length in feet of the first five internodes beginning at breast height.

Statistical Analysis

Multiple linear regression techniques were used in SAS 9.1 (2003) to identify the soil and site properties that were significantly related to white pine SI. Transformations of the independent variables were used to linearize the data based on known relationships. Multicollinearity assessments were made using variance inflation factors (VIF’s) (Montgomery et al., 2001). Points with large influence or leverage on the model were identified using various influence statistics (Montgomery et al., 2001). Point distributions, normality, and homogeneity of variance of the data were all analyzed using residual plots, stem-leaf plots, and normal probability plots (SAS 9.1, 2003). Mallows’ C(p) statistic was used as a selection procedure to derive a list of the best models (Montgomery et al., 2001). Sufficiency curves were developed for all variables used in the final model, using a compilation of research results and previously developed curves. Importance factors (IF) for each variable were calculated using the absolute value of standardized coefficients (Montgomery et al., 2001), and normalizing the values from 0 to 100%.

Results and Discussion

General Model

Sufficiency curves were developed for soil and site properties that we believe had significant effects on tree growth. Curves for five properties are presented. A sufficiency curve was developed for pH (Fig. 1), similar to the one used by Andrews (1992), and was adjusted using research results from Gale et al. (1991) and Torbert et al. (1990). A pH between 4.5 and 5.8 is considered optimal for white pine and was assigned a sufficiency of 1.0, while a linear decline on each side of the optimal plateau results in a pH of 3.0 and 8.0, having a sufficiency of 0.2. Neill (1979) and Andrews (1992) produced sufficiency curves for D_b, both of which decline in sufficiency after a critical D_b. The sufficiency curve developed in this study follows the same pattern but is shifted slightly to the left to accommodate our method of soil density assessment (Fig. 2). Mine soils typically have less structure and porosity and fewer interconnected pores, which may lead to adverse soil moisture and aeration conditions at lower D_b values. Actual D_b values are associated with the classes of soil density used in this study.

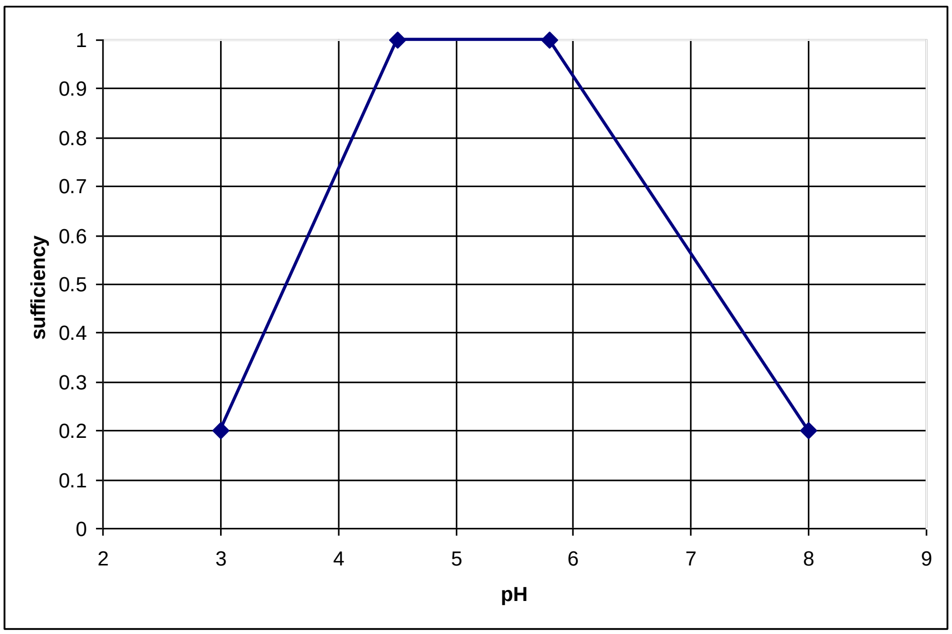

Figure 1. A sufficiency curve for pH was developed based on research by Andrews (1992), Gale et al. (1991), and Torbert et al. (1990). The optimum pH range for white pine on mine soils is between 4.5 and 5.8.

To our knowledge, no sufficiency curves for soil texture have been developed. For a first approximation, we based a soil texture sufficiency curve (Fig. 3) on mine soil research by Burger and Zipper (2002), and used findings by Lancaster and Leak (1978), who reported on white pine growth on native soils. Heavy clay soils are known to be unproductive for white pines, and extremely sandy soils will lead to droughty conditions. A sandy loam texture is optimal for pine growth; this textural class falls within the range of silt + clay % that has a sufficiency of 1.0. Ranges of silt + clay % overlap among the soil texture classes.

The coarse fragment sufficiency curve is based on research by Rodrigue and Burger (2004). A linear relationship with increasing CF contents and decreasing sufficiency levels is expected at CF content greater than 35 % (Fig. 4).

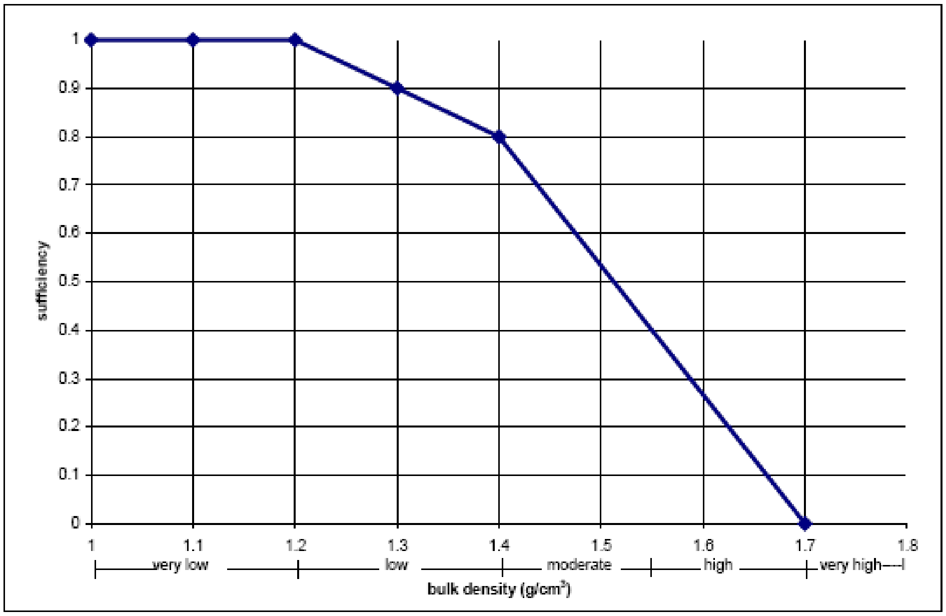

Figure 2. Bulk density sufficiency curves developed by Andrews (1992) and Neill (1979) were modified to accommodate the method of density measurement used in this study, and to account for differences in mine soils compared to native soils. Soil density classes used in this study were defined by a range in bulk density.

The sufficiency of potential rooting depth was defined by Equation 4 (Gale, 1987):

$$Y = 1 - \beta^{d} \qquad \textbf{(4)}$$

where Y = cumulative root fraction from the soil surface to soil depth d (cm); and $\beta = 0.96$, the estimated parameter used by Torbert et al. (1994) for white pine.

This sufficiency curve attributes greatest importance to the thickness of the surface soil layer, with the relative importance of rooting in subsoil layers decreasing exponentially with depth (Fig. 5).

A general productivity model (Equation 2) incorporating five of the most important soil properties for white pine productivity on mine soils is:

$$PI = (pH \text{ x texture x density x } CF)^{1/4} \text{ x depth} \qquad \textbf{(5)}$$

where PI = Productivity Index; pH = sufficiency of pH; texture = sufficiency of texture; density = sufficiency of soil density; CF = sufficiency of coarse fragments; and depth = sufficiency of rooting depth, which is equivalent to WF in Equation 2.

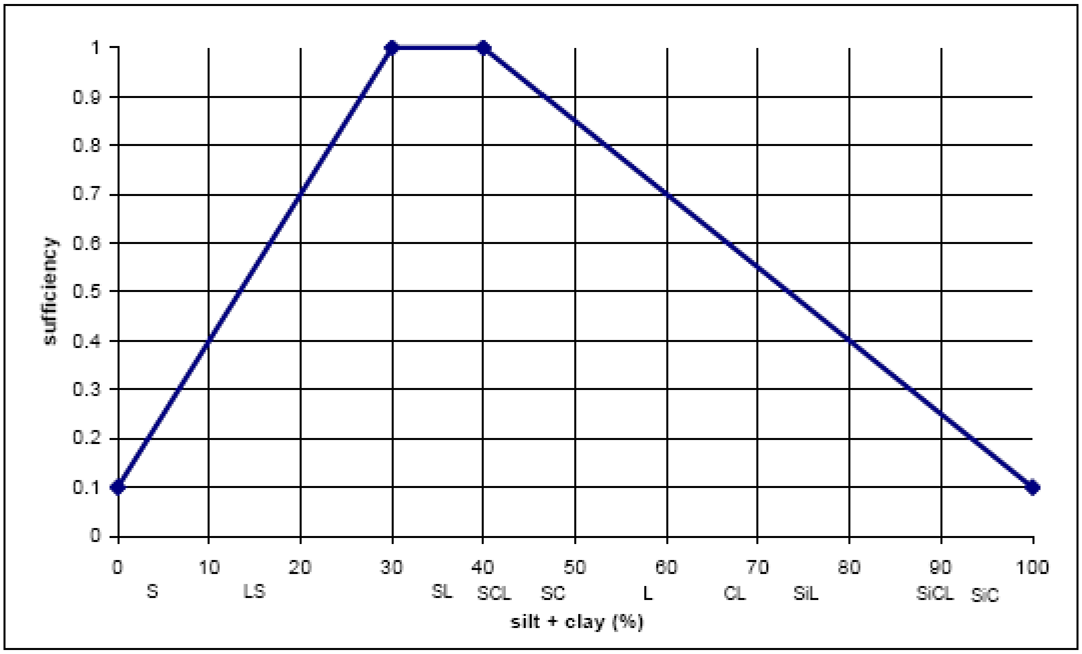

Figure 3. A sufficiency curve for texture and its influence on white pine growth on mine soils in the Appalachian region was developed based on research from Burger and Zipper (2002) and Lancaster and Leak (1978). Silt + clay % overlaps among texture classes.

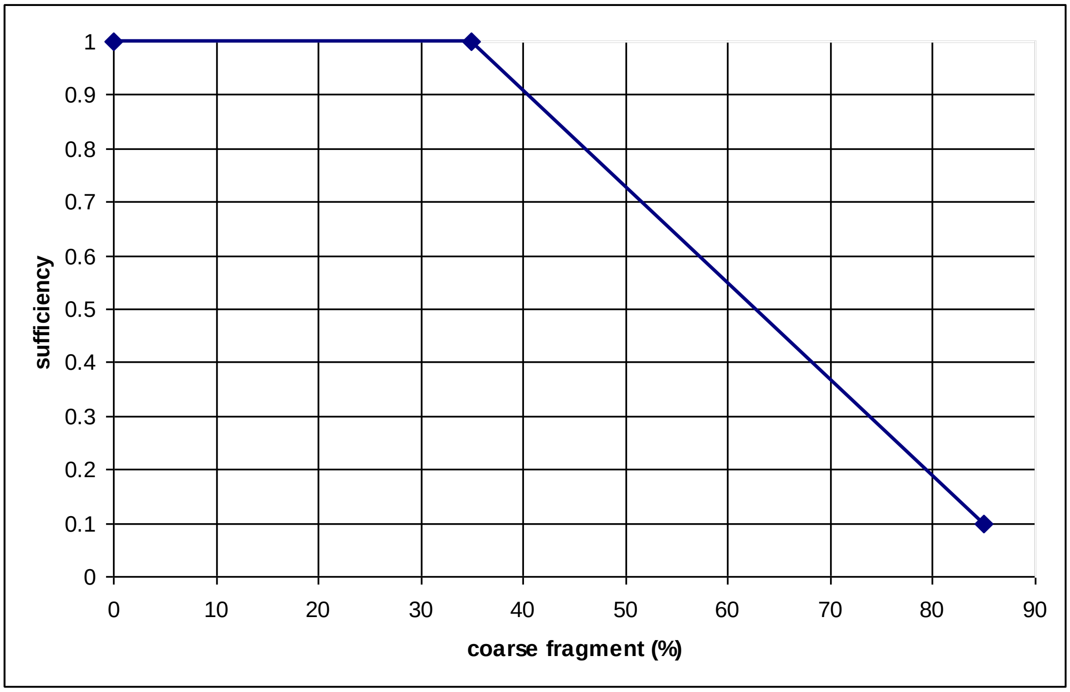

Figure 4. Coarse fragment sufficiency as a function of coarse fragment content (%). White pine growth is expected to decline when coarse fragment content exceeds 35%.

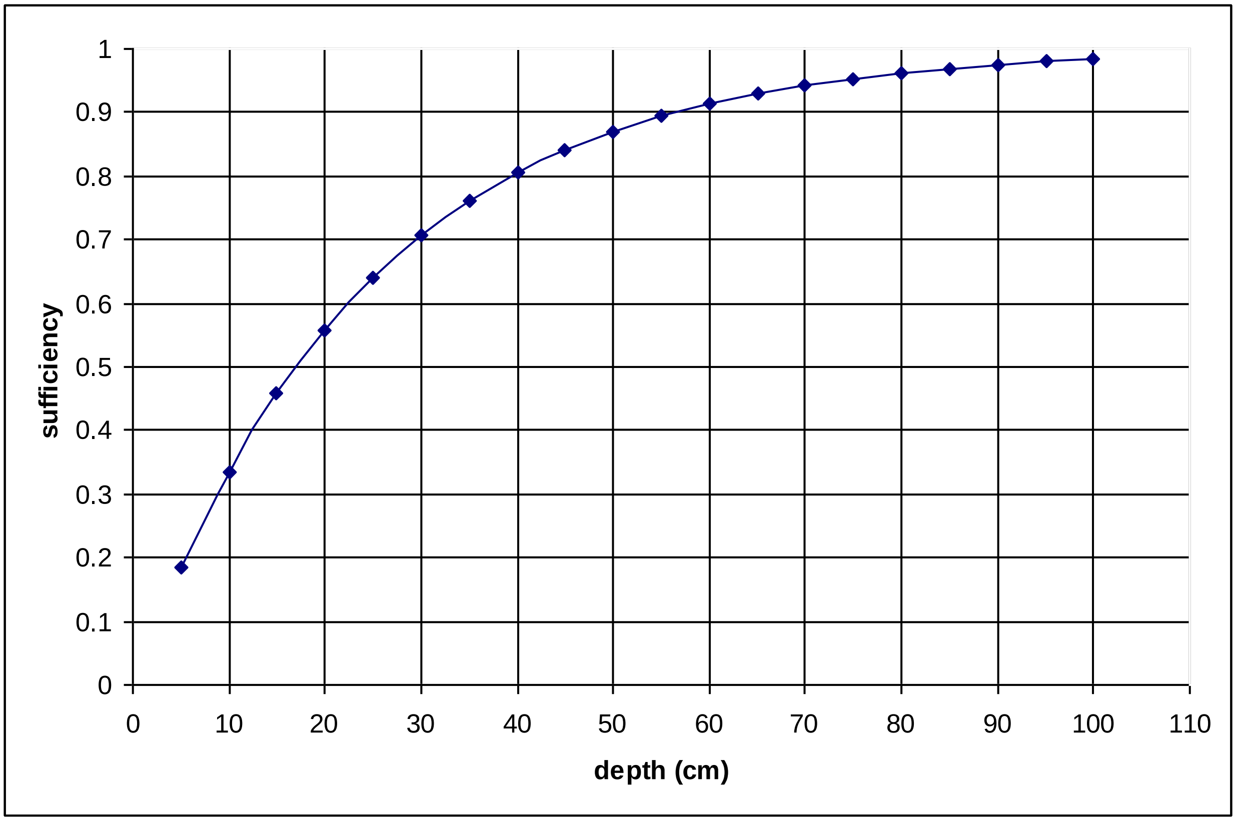

Figure 5. Sufficiency of rooting depth declines exponentially with decreasing depth.

A PI was calculated for each of the 52 white pine sites using the measured values for pH, texture, density, CF, and depth. PI values were regressed with white pine SI to determine the extent to which the general PI model correlated with SI. The fit of the general PI model to SI of the validation sites resulted in an R^2 value of 0.63 (Fig. 6). This shows that the general soil-based PI model could be used in lieu of SI to estimate the productivity of mined land for white pine.

White Pine-Specific Model

The general model (Equation 5) calculates a geometric mean for all soil property sufficiency levels, which assumes that each has the same level of importance on the PI and subsequent tree growth. For a given tree species, it is likely that some soil properties have a greater or lesser influence than other soil properties, so the model could be improved if each property was weighted based on the extent to which each influenced tree performance. A white pine-specific productivity model was developed using regression relationships between white pine SI and soil properties found on the 52 measured sites.

Site index was regressed with all soil and site variables. Three of the original 52 data points were discarded because they were extreme outliers, or had large influence and leverage on the model determined by influence statistics. The pH variable was squared to linearize the known relationship of tree growth as a function of pH for the range observed. The CF and slope variables were log transformed.

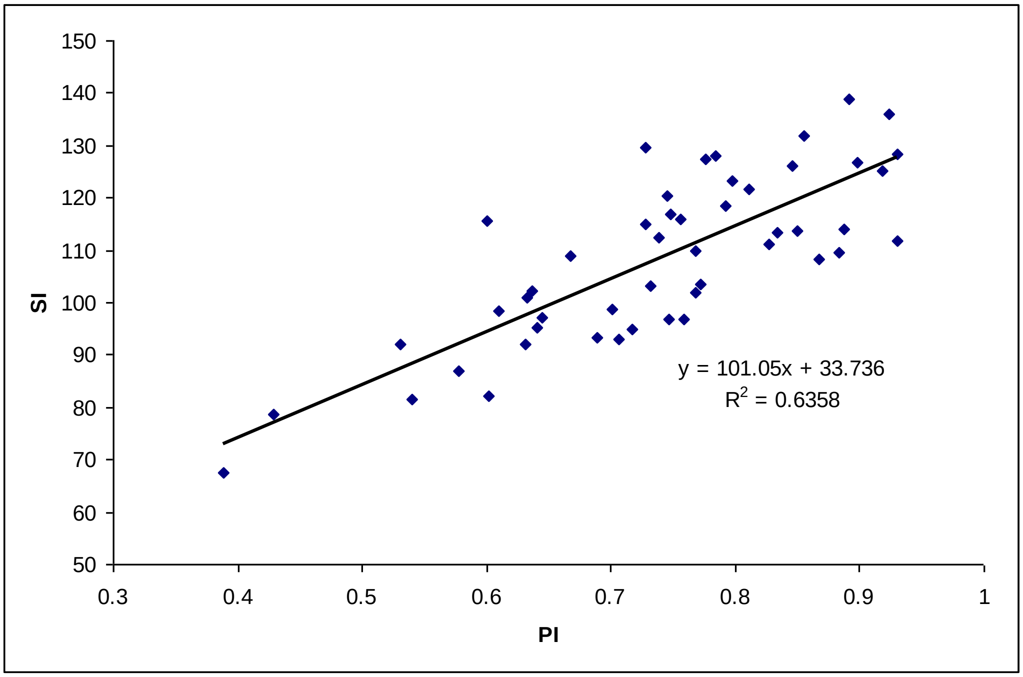

Figure 6. The relationship between white pine site index and mine soil productivity (PI) calculated from general tree/soil relationships.

Soil density was the most important variable affecting tree growth (Table 1), as predicted by the work of Daniels and Amos (1981) and Torbert and Burger (1990). A regression of SI and density alone resulted in a R^2 of 0.53, with higher densities having lower SI values. Rooting depth was the second most influential variable, which agrees with the results reported by Andrews et al. (1998) and Torbert et al. (1988b). Rooting depth is not expected to be as important in seedling survival and early growth when the root system is not yet fully developed. Textures of sandy loam and loam were the only two recorded across all of the validation sites. This may have led to a biased evaluation of the texture variable, but the variable was significant (Table 1) and an influential property according to the studies of Burger and Zipper (2002). pH by itself was insignificant at the $p \leq 0.10$ level, but it did improve the overall model. The soil reaction ranged from pH 4.3 – 8.0 with the distribution of values skewed toward lower levels. Most native trees in the Appalachian Mountains grow where pH is 5.5 or less (Skousen et al., 1994) but some species can grow well at more neutral pH values.

Percent CFs ranged from 10% to 43%, which was lower than other studies, possibly due to the increased age and weathering time of the sites. Percent CFs was negatively correlated with SI and was an insignificant variable. Rodrigue and Burger (2004) found CF content to be negatively correlated with SI of white oak, and the same was expected in this study. However, the low levels of CFs in this study may not be in the range in which limitations occur, but they do affect water holding capacity and total rooting volume, both of which are extremely important to forest productivity (Aydelott, 1978). CF content may be more important on younger sites for seedling survival when trees have not yet developed an extensive root system, available soil moisture is limiting, and most CFs have not undergone physical weathering into fine soil material.

Table 1. Standardized coefficients, importance factors, and significance values for the independent variables used in the final model (Equation 6).

Variable	Standardized Coefficient	Importance Factor	*p*-value
density	-0.54789	0.44	<0.0001
rooting depth	0.34989	0.28	0.0004
texture	-0.25135	0.20	0.0039
pH	-0.10393	0.08	0.2167

EC was not significantly correlated with white pine in this FSQ model, contrary to the results of Andrews et al. (1998) and Rodrigue and Burger (2004). In a study on 10-year-old white pines by Torbert et al. (1988b), the highest EC level recorded was 1.7 dS/m and it corresponded to a tree size of only 1.18 m. This suggests that a critical value of 1 dS/m is associated with white pine productivity and all EC values in this study were lower than 1 dS/m. All textures were sandy loam and loam, which have been reported to have low EC values, while finer textures are more commonly associated with high EC levels (Rodrique and Burger, 2004). The ages of the sites were all between 10 and 18 years, allowing any initially high salt levels to leach over time. The use of the EC variable for younger sites (< 5 years) may be beneficial for predicting tree survival.

The color variable was not significant in the forest site quality model, but an observation of color may provide insight to some soil properties such as degree of oxidation and weathering. In this study slope was insignificant, but we believe that it could serve as a surrogate for soil density, as flatter slopes tend to have denser soil (Andrews et al., 1998).

Aspect was not used in this model because there was no correlation with SI values. This is not biologically reasonable and is contrary to previous research (Burger et al., 2002). The lack of compaction and increased rooting depth on steeper slopes, regardless of the aspect, is assumed to compensate for hotter and drier conditions. A simple description of rock type was not significant in the model; color, texture, and pH sufficiently characterized the different rock types.

The C(p) selection procedure indicated that a model with only the variables of texture, density, and rooting depth was the best model. The addition of the pH variable resulted in the best four-variable model, with a coefficient of determination (R^2) of 0.71 and an adjusted R^2 of 0.68. This model was chosen because of the known importance of pH on forest productivity of mine soils (Torbert et al., 1990). The VIFs indicated that no significant multi-collinearity problems existed.

A relative importance factor (IF) was calculated for each soil property in the regression model. Importance factors were calculated by normalizing the standardized coefficients from 0 to 1. Density was the most important soil property that affected white pine growth in this data set, followed by rooting depth, soil texture, and soil pH (Table 1). The sufficiency level of each soil property was weighted by its relative importance (IF) as shown in the following additive PI model:

$$PI_{wp} = ((pH*IF) + (texture*IF) + (density*IF) + (depth*IF) \qquad \textbf{(6)}$$

where PI_{wp} = white pine-specific Productivity Index; pH = sufficiency of pH; texture = sufficiency of texture; density = sufficiency of soil density; depth = sufficiency of rooting depth; and IF = importance factor for each soil property (Table 1).

A regression of PI_{wp} with SI (Fig. 7) shows that weighting the sufficiency values based on the relative importance of each soil property improved the mine soil productivity estimation. The R^2 of the PI_{wp} versus SI relationship was 0.69, compared with 0.63 for the general PI model.

For management purposes, foresters commonly divide the site quality gradient found across the landscape into site quality classes. The PI_{wp} was used to separate five categories of white pine site quality class (FSQC), with FSQC (I) being the most productive and FSQC (V) being the least productive (Table 2). No white pines were found in this study that survived in soil-site conditions of FSQC (V). The SI breakpoints for white pine were based on the research of Doolittle (1958), who found the average SI for white pine on natural soils in the southern Appalachians to be 24 m (80 ft). His study showed an SI range from 20-30 m (66-98 ft).

Table 2. The productivity index (PI) is associated with forest site quality classes (FSQC) and predicted site index (SI, tree height at age 50).

PI	FSQC	SI (ft)
≤0.4	V	< 65
0.41 - 0.55	IV	65-79
0.55 - 0.7	III	80-94
0.71 - 0.85	II	95-110
>0.85	I	> 110

The following example demonstrates use of the FSQ model: After the evaluation of a certain site, a pH value of 6.0, a silt + clay % of 60 %, 45 % CFs, a moderate density level, and a rooting depth of 57 cm were observed. Therefore, (0.93*0.08) + (0.7*0.20) + (0.5*0.44) + (0.9*0.28) = 0.69 = PI. According to Table 2, this value falls on the high end of the range, for a FSQC of III; white pines growing on this site will likely have a SI = 90-95.

Other Models

Our final PI_{wp} model appears to be a good estimator of white pine FSQ on older surface mines. However, some reclamationists may want to plant trees immediately following final reclamation. We believe that the addition of the CF, EC, rock type, and color variables would be beneficial for sites less than five years old. Sites older than this have already been through the initial weathering stages during which salts are leached and easily weathered rocks have broken down into soil fines.

Native hardwood tree species may be preferred on some reclaimed mined sites. Hardwood species may respond differently to mine soil properties compared to white pine (Burns and Honkala, 1990). Therefore, it would be important to calibrate sufficiency curves for hardwoods, to the extent possible, based on published species/mine soil relationships. Hardwoods have only recently been used for post-SMCRA reforestation in the Appalachian region, and very few sites exist for model validation. However, based on the success of this initial FSQ model developed for white pine, it appears that an adequate general model could be developed for hardwoods as well. Furthermore, hardwood SI can be estimated with site index comparison curves developed for several Appalachian species (Doolittle, 1958).

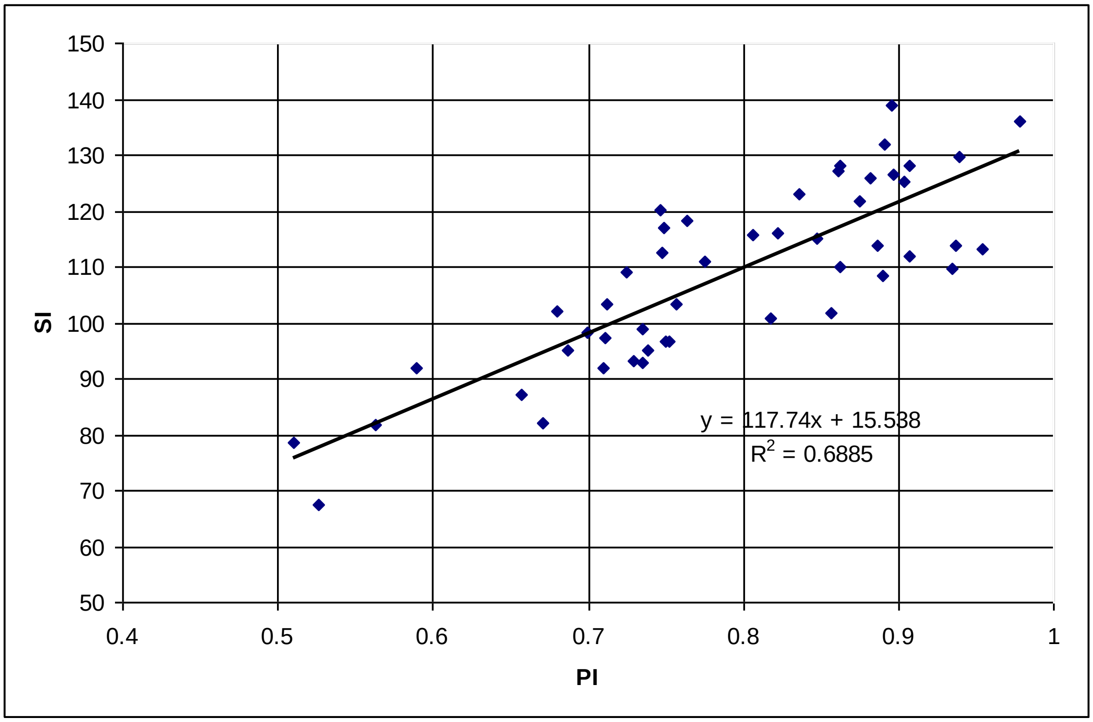

Figure 7. A regression of the white pine-specific productivity index (PI_{wp}) with site index (SI, tree height at age 50) of white pine.

Conclusion

Many chemical and physical soil properties, as well as site factors, influence tree growth and forest productivity on mined land. Successful establishment of a productive forest on reclaimed mined land can provide economic benefits through wood production, wildlife habitat, watershed protection, and carbon sequestration. The SMCRA of 1977 requires that reclaimed land be equally as or more productive than pre-mined conditions. However, since the passage of this law, few productive forests have been established due to poor mine soil conditions, lack of incentives for mine operators to plant trees, and inability to estimate mine soil quality for forests.

Our work shows that FSQC ratings based on field-measured soil properties can be used to predict potential forest productivity, which will aid in forest management prescriptions. Our work showed that soil pH, texture, density, and rooting depth were the most influential properties for white pine growth on post-SMCRA reclaimed surface mines, with density being the most important. Other factors may be more influential on younger sites or on sites for which native hardwoods are the intended forest type.

Our FSQ classification model should aid mine operators, foresters, and landowners in determining the productive capability of mined land, in making management decisions, and in reducing the risk associated with planting trees on mined land.

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